Title: **Behaviour of Concrete Structural Members Subjected to Air Blast Loading**

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(FIRST PAGE OF ARTICLE)

Numerical analysis is a suitable tool in the design of complex reinforced concrete structures under extreme impulsive loadings such as impacts or explosions at close range. Such events may be the result of terrorist attacks. Reinforced concrete is commonly used for buildings and infrastructures. For this reason, the ability to accurately run numerical simulations of concrete elements subjected to blast loading is needed. In this context, reliable constitutive models for concrete are of capital importance. In this research numerical simulations using two different constitutive models for concrete (Continuous Surface Cap Model and Brittle Damage Model) have been carried out using LS-DYNA. Two experimental benchmark tests have been taken as reference. The results of the numerical simulations with the aforementioned constitutive models show different abilities to accurately represent the structural response of the reinforced concrete elements studied.

INTRODUCTION

In the design of concrete structures to resist the effects of explosions, impacts or other severe dynamic loads, it is not practical to consider a structural response in the elastic range only. Structural elements that may be subjected to such loads should be allowed to deform plastically, which better utilizes the energy-absorbing capabilities of the element. A certain amount of damage is therefore usually accepted when designing protective structures or buildings that need to resist a certain amount of dynamic loads. The amount of accepted damage depends on the structure's level of protection.

It is well known that the load capacity of concrete elements increases when subjected to dynamic loads compared to the case of a static load. However, real events have shown that highly intense loads from blast at close range may cause local shear failures in concrete structures. This is a brittle mode of failure that severely limits the load capacity of an element. Typically, shear failure appears relatively early in the structural response, before any important plastic deformations have taken place and can cause progressive collapse of the structure. Apart from real events, shear failures have also been experimentally observed in air blast tests [1-5].

In order to analyze the response of concrete structures undergoing large plastic deformations and different failure modes, the use of numerical simulations has proven to be a suitable tool. Several material models have been developed for the prediction of concrete structures at high strain rates and validation of these models with experimental data as reference is vital. The aim of the investigation presented in this paper was to perform non-linear simulations of reinforced concrete beams and slabs subjected to blast loads with the use of LS-DYNA [6]. Two material models, i.e., the Brittle Damage Model (BDM) and the Continuous Surface Cap Model (CSCM), in the LS-DYNA material library were evaluated against two experimental benchmarks previously developed by the authors. The work has been focused on comparing deformations, crack patterns and failure modes.

EXPERIMENTAL PROGRAM

Shock Tube Tests

Reinforced concrete beams with a cross section of 0.30 × 0.16 m (width × height) and 1.70 m long were tested. The beam considered in the present paper was of conventional concrete with a compressive strength at 28 days of 43 MPa with respect to ϕ150 × 300 mm cylinders. The beam reinforcement, shown in Figure 1, consisted of rebars of grade B500BT with a nominal yield strength of 500 MPa. A more detailed description of the experimental program can be found in [3, 5].

The air blast tests were conducted in a shock tube at the testing ground of the Swedish Defence Research Agency (FOI). The shock tube is designed to simulate shock waves originating from an air blast and has an internal rectangular cross section of 1.20 × 1.60 m in the vicinity of the test area. The concrete beams were assembled in a test rig positioned at one end of the tube. Due to the rig configuration, the beams were free to rotate at both supports during the dynamic response. The free span between the supports was 1.50 m.

The explosive charge, shaped as a sphere, was positioned at the center of the tube's cross section and at a distance of 10 m from the beam. At this distance theblast pressures can be regarded as equally distributed across the beam surtface. The test configuration prevented any blast pressure leakages to the rear face of the beams. The instrumentation of these tests consisted of gauges measuring the reflected pressures, load cells at the supports, and a deflection gauge and an accelerometer at mid-span of the beam, see Figure 2. Strain gauges on the concrete surface and on one rebar were also used in a few tests.

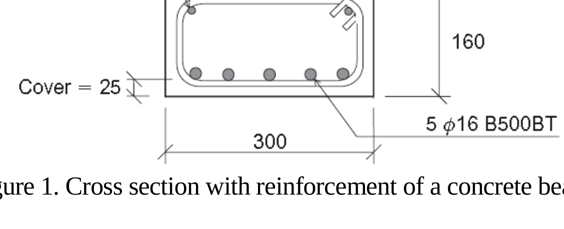

Figure 1. Cross section with reinforcement of a concrete beam.

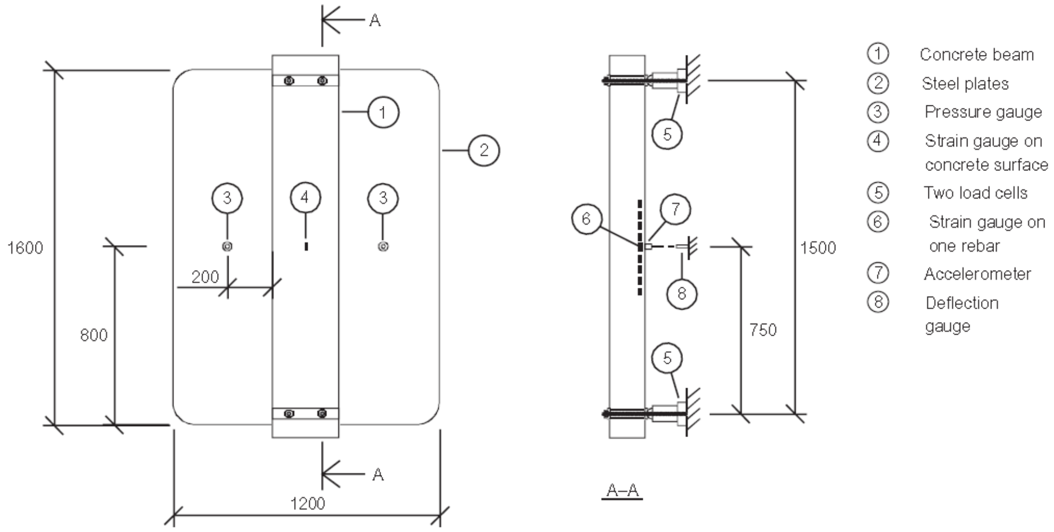

Figure 2. Instrumentation of the shock tube tests.

Open Air Detonations

A series of blast loading experiments on concrete targets were performed with the aim of providing experimental data for the development and adjustment of numerical tools needed in the modeling of concrete elements subjected to blast. For further details about the experimental campaign, the reader is addressed to [1, 2].

A steel frame was built to bear the concrete samples that were to be tested under blast loading. The steel frame supported the concrete specimens and consisted of four vertical columns tied horizontally with beams that also withstood the concrete slabs. The concrete targets were placed on vertical planes equidistant to the explosive. The placement of the explosive in the center of the steel frame assured that all the slabs received the same shock wave pressure at the same time. This set-up allows up to four specimens to be tested with every detonation.

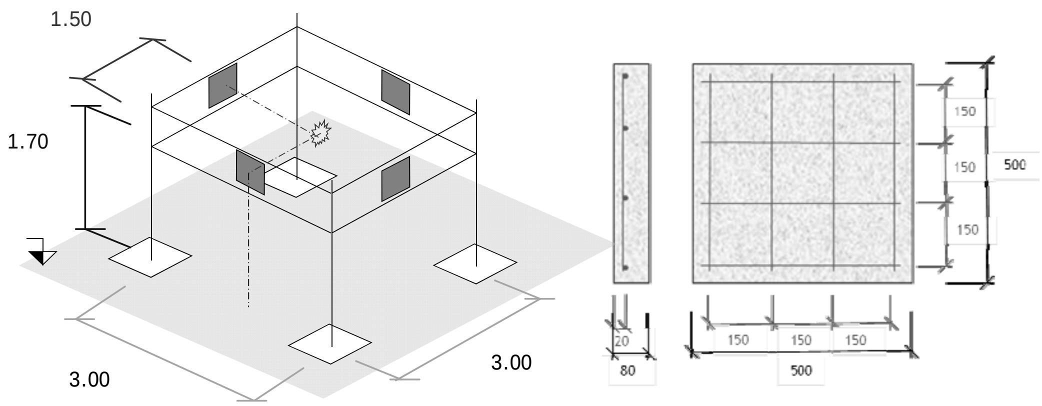

Figure 3. (a) Test set-up (b) Geometry of the slabs.

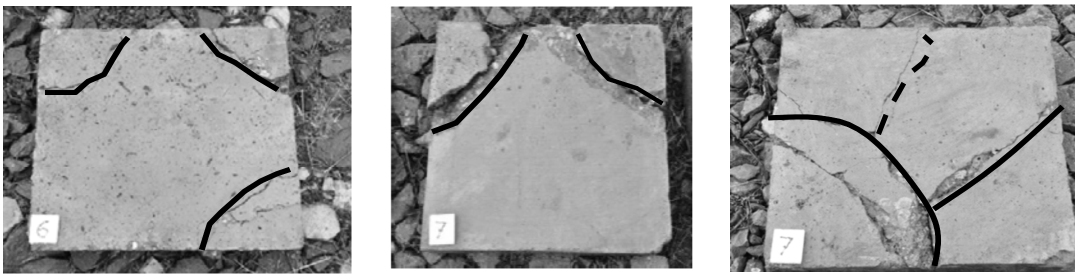

Figure 4. Open air detonations results. Shear cracking is highlighted in black continuous line, while bending cracking is highlighted in black dashed line.

The distance between columns was 3.00 m, thus making a 1.50 m stand-off distance from the explosive to the samples. The height of the horizontal beams above ground was 1.45 m and 1.95 m, see Figure 3 (a).

The concrete of the slabs were of 58 MPa of compressive strength at the time of testing. Two tests with 5 kg TNT equivalent have been performed, which represent a total of six concrete slabs. The geometry of the plates is shown in Figure 3 (b), which also shows the reinforcement on their rear side with steel reinforcing bars with a diameter of 6 mm in both directions and of steel grade B 500 S.

The explosive used in the experimental program has been the commercial compound Goma 2 ECO. Its combustion heat corresponds to 89% of the energy release of 1 kg TNT. An amount of 5.712 kg Goma 2 ECO was used for the tests, whose energy release is equivalent to a 5.08 kg TNT explosion.

NUMERICAL SIMULATIONS

The experiments summarized in the previous sections were simulated using LS-DYNA v.761 [6], which is an explicit finite element code. The research focused on the constitutive modeling of concrete under extreme loading, with high pressures under impulsive events and complex stress combinations. The two different material models for concrete that were used, are briefly discussed in the first two sections. The simulation results are discussed in the sections that follow.

The Continuous Surface Cap Model

The Continuous Surface Cap Model (CSCM) is an elasto-plastic damage model with rate effects for concrete implemented into LS-DYNA under material number 159. A more detailed description can be found in [7, 8].

It is a model for concrete under high strain rates, in which the material behaves linearly elastic in the low stresses regime. When a threshold value of stress is reached plastification occurs according to a yield criterion that takes the three stress invariants into account. The failure surface defined is closed by a hardening cap in the high stresses domain, see Figure 5. The cap surface presents a smooth or continuous intersection with the failure surface, providing numerical stability.

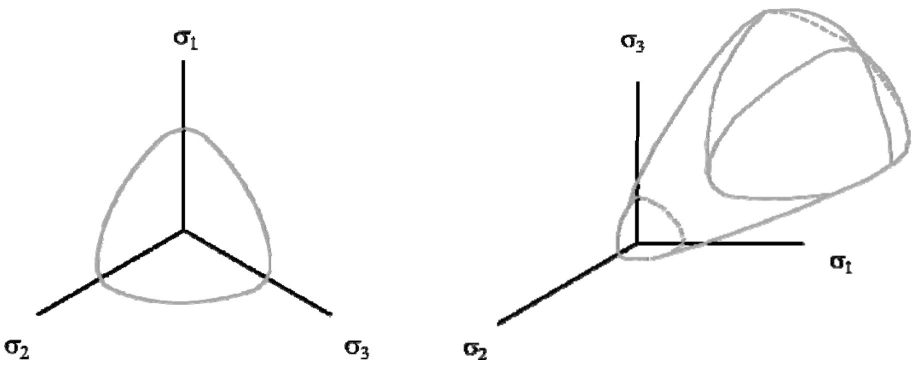

Figure 5. (a) Tensile failure surface in the deviatoric plane in CSCM. (b) Schematic depiction of yield surface in CSCM.

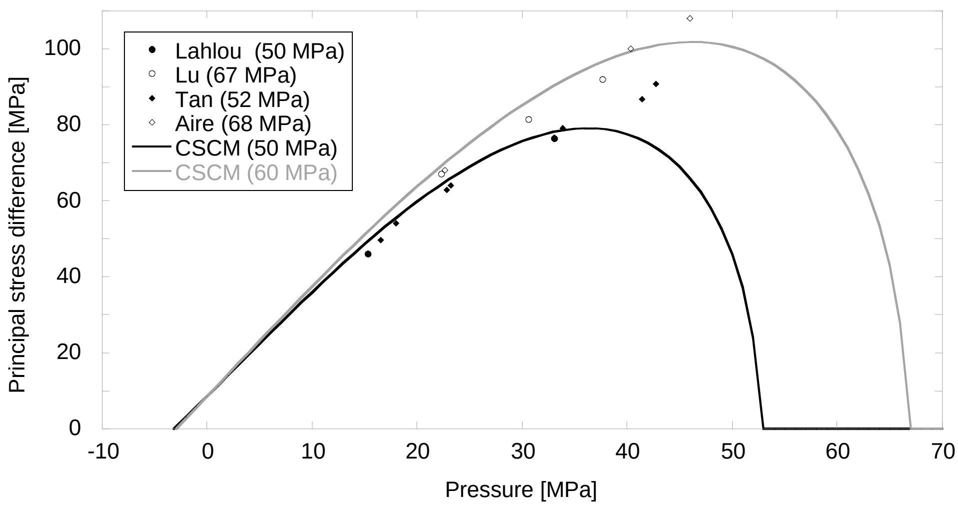

Figure 6. Shear and cap surfaces for concrete of 50 and 60 MPa of uniaxial compressive strength.

A section of the yield surface along its meridonal plane is depicted in Figure 6 for the two values of compressive strength of concrete used in this research. The experimental results for tri-axial testing of different strengths concretes [9-12] are also plotted.

Softening of concrete is modeled via a damage formulation that accounts for both strain softening and modulus reduction.

The strain rate effects (material strength increase with increasing strain rate) are modeled with a Duvaut-Lions viscous material formulation. Thus, strain rate dependence for tensile and compressive states of stress, as well as for fracture energy, is included in the model.

The Brittle Damage Model

The Brittle Damage Model (BDM) is described in detail in [13] and is available in LS-DYNA under material number 96. It can be briefly described as an anisotropic brittle damage model, in which smeared cracks are formed under tensile stresses. Compressive failure is available through a Von Mises yield criterion.

In contrast with CSCM, the BDM is of a much simpler nature. Failure under tensile stresses occurs according to the Rankine criterion, that is, when the first principal stress on the material exceeds a threshold value, namely its tensile strength.

After failure in tension, a smeared crack field is fixed in the material. Tensile forces across the crack field are limited to a value given by an exponential law. The stress across the crack decays with the increasing deformation of the crack. Shear stresses between the crack tips are also limited to a value that decreases with increasing deformation.

Strain rate dependency is taken into account through material viscosity. Viscous behavior is implemented as a Perzyna regularization method. Thus, strain rate dependence for tensile and compressive states of stress, as well as for fracture energy are included in the model.

Shock Tube Tests – Modeling and Results

The concrete beams and steel rebars were meshed with 5×5×5 mm solid (brick) one integration point elements, resulting in a total of 638000 elements. Linear springs were set in the common nodes of concrete and tensile reinforcement to represent the bond between concrete and steel. The response of the springs was set to follow the spring law according to [14], see Figure 7 (b). The material for the supports was taken as linear elastic, were modeled with the same conditions as in the real test and with a friction of 0.05 between concrete and the steel supports. The bolts at each support that were used to tie the beams to the supports during the tests were also modeled.

Concrete was simulated using the aforementioned material models, namely CSCM and BDM. The mechanical properties of concrete are given in Table I, which have been taken from the materials characterization carried out in [5]. The extended input of CSCM has been used, and the full set of parameters input has been estimated through numerical compressive and tensile tests.

TABLE I. MECHANICAL PROPERTIES OF CONCRETE

Variable	Value
Density [kg/m^3]	2300.00
Elasticity modulus [MPa]	30826.00
Compressive strength [MPa]	50.00
Tensile strength [MPa]	4.50
Poisson's ratio [-]	0.15
Fracture energy [N/m]	130.00

TABLE II. MECHANICAL PROPERTIES OF STEEL

Variable	Value
Density [kg/m^3]	7850.00
Elasticity modulus [MPa]	203000.00
Yield stress [MPa]	580.00
Poisson's ratio [-]	0.30

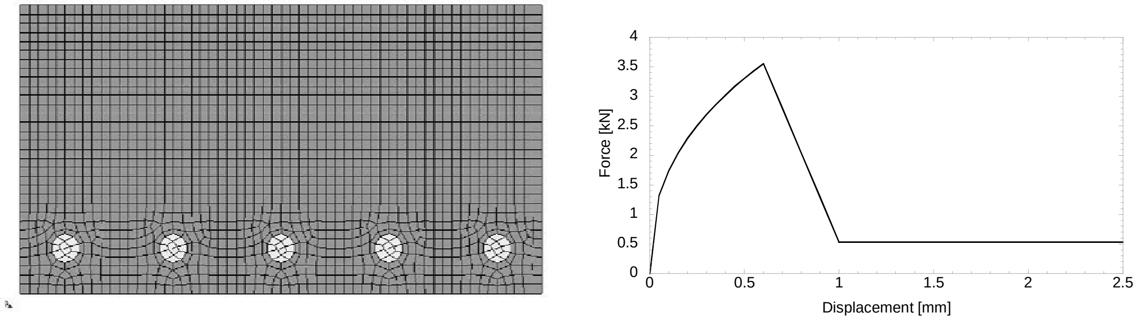

Figure 7. (a) Cross section of the beam. (b) Bonding law.

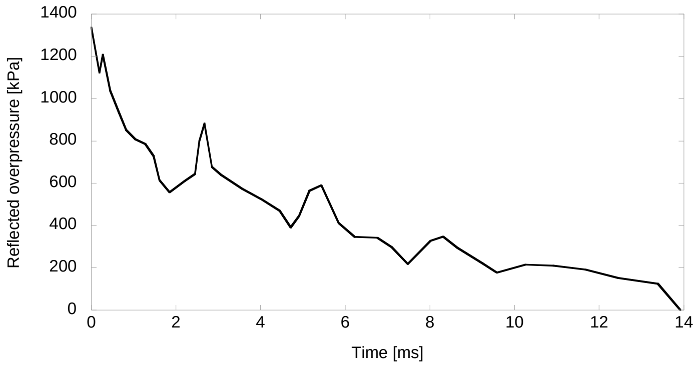

Figure 8. Reflected pressure applied in the analysis of the beams.

The results obtained from the simulations show good correspondence with the experimental results both in cracking patterns and deflection, see Figures 9 - 12. Both material models shows flexural cracks along the beam and diagonal tension cracks in the vicinity of the supports. This indicates that the beam is failing in a diagonal shear mode in both simulations.

Steel rebars were modeled using the Piecewise Linear Plasticity model, which is an elastic-plastic material model with strain hardening. The parameters input are given in Table II. Further on, true stress - strain hardening relations obtained from the materials characterization have also been used.

Air blast loading was imposed by applying directly the reflected pressure–time history that was measured during the tests, see Figure 8.

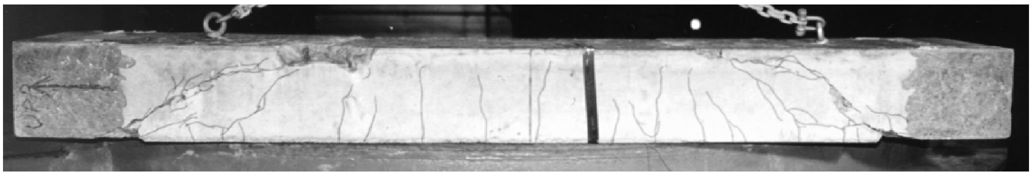

Figure 9. Beam B40-D4 after test.

Figure 10. Cracking pattern predicted by CSCM. The scale next to the simulated beam is a measure of the amount of cracking in the concrete.

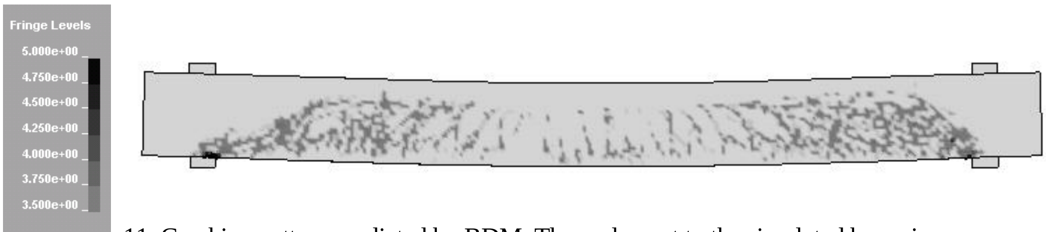

Figure 11. Cracking pattern predicted by BDM. The scale next to the simulated beam is a measure of the amount of cracking in the concrete.

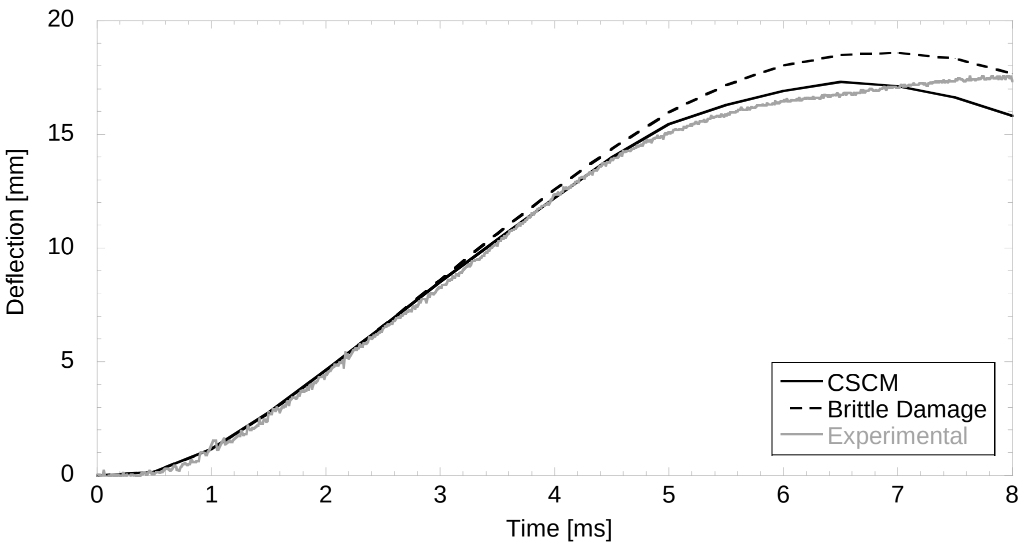

Figure 12. Comparison of load – deflection curves predicted by CSCM and BDM with experimental results.

Open Air Detonations – Modeling and Results

The concrete slabs were meshed with 4×4×4 mm one point integration solid (brick) elements, resulting in a total of 546000 elements. The steel rebars were modeled with 1500 truss elements of 4 mm length. In this case, bond between concrete and rebars was modeled using common nodes for steel and concrete meshes, which is equivalent to assuming perfect bonding between concrete and rebar. Perfect bonding was preferred in the simulations of the slabs, as no bonding failures were detected in the experimental program.

On the date of casting of the slabs, two unreinforced concrete slabs were also cast and stored for use in material characterization of the concrete. Samples (dimensions 150×66.5×66.5 mm) for characterization of concrete were taken from these slabs. The production of the samples was made through sawing with a wet cutting machine. Tests for characterization of fracture energy, uniaxial compressive strength and indirect tensile strength were carried out on the specimens.

From the uniaxial compressive tests the constitutive relationship was obtained, see Figure 13. This figure also shows the simulation results of the compressive tests using both concrete models. More details about the material characterization are given in [2].

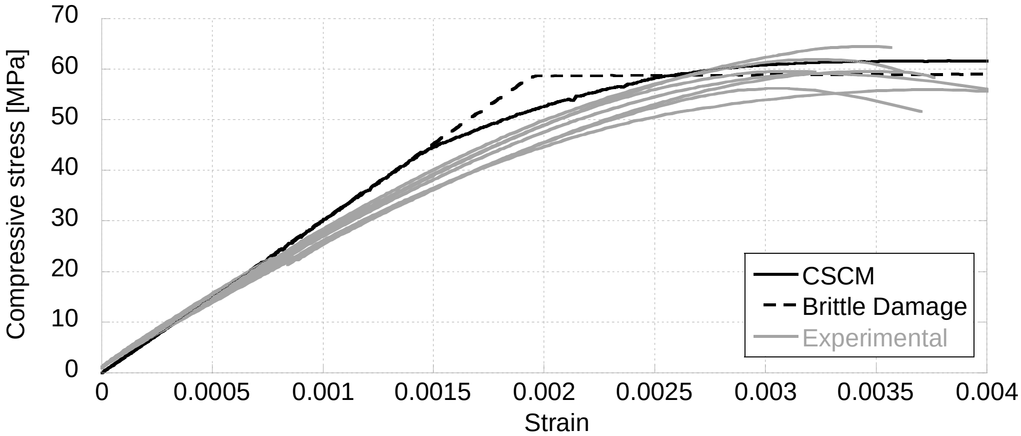

Figure13. Comparison of constitutive relationships between CSCM, BDM and experimental results.

TABLE III. MECHANICAL PROPERTIES OF CONCRETE

Variable	Value
Density [kg/m^3]	2283.00
Elasticity modulus [MPa]	30085.00
Compressive strength [MPa]	58.82
Tensile strength [MPa]	4.40
Poisson’s ratio [-]	0.20
Fracture energy [N/m]	215.00

TABLE IV. MECHANICAL PROPERTIES OF STEEL

Variable	Value
Density [kg/m^3]	7850.00
Elasticity modulus [MPa]	205000.00
Yield stress [MPa]	500.00
Poisson’s ratio [-]	0.30

The material parameters input for the concrete model are given in Table III. An elastic-plastic material model with hardening (Piecewise Linear Plasticity model) was used for the reinforcement with the parameters given in Table IV.

Loading of slabs was imposed by applying the reflected pressure–time history that was measured by piezoelectric pressure gauges during the tests [1, 2], see Figure 14.

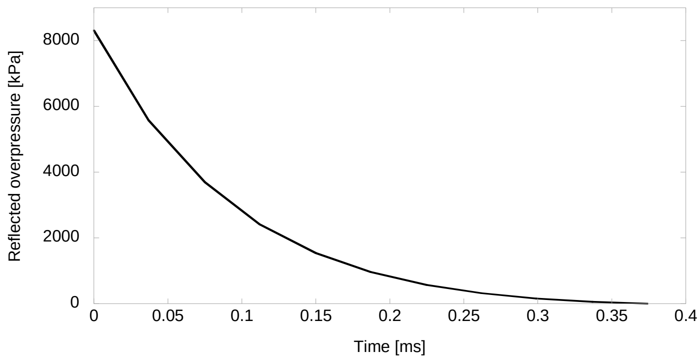

Figure 14. Reflected pressure applied in the analysis of the beams.

In the experimental results, two different failure modes were clearly observed after the tests, despite the experimental scattering in crack pattern and damage level. These failure modes are of shear failure, depicted by the circular cracks in the vicinity of the supports, and of bending failure represented by cracks parallel to the sides of the slabs. These failure modes are shown in Figure 4.

The results obtained from the simulations vary depending on the material model used. While the CSCM predicts a pure bending failure mode, the BDM in turn only shows shear cracking in the vicinity of the supports, predicting shear failure, see Figures 15 and 16. The BDM simulation shows a similar pattern of diagonal tension cracks as was observed in the tests. Even though the simulation with the use of CSCM shows fully developed flexural cracks at mid-span, diagonal cracks also are initiated close to each support.

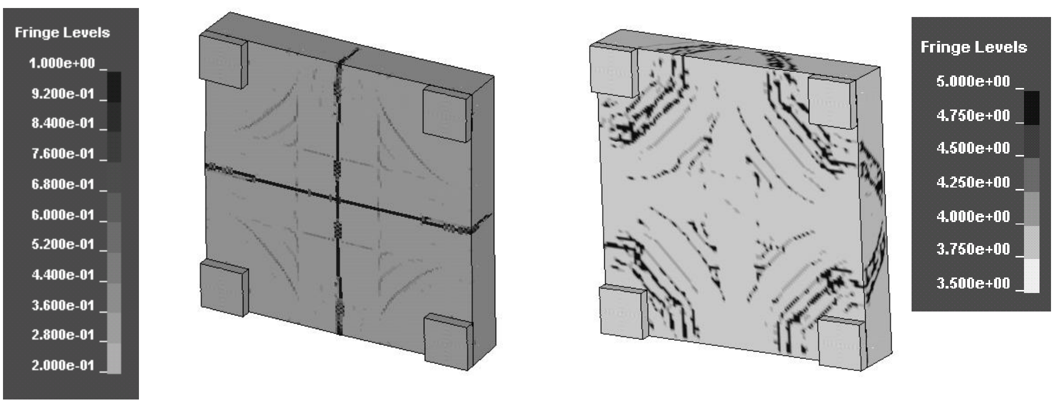

Figure 15. (a) Cracking pattern predicted by CSCM. (b) Cracking pattern predicted by BDM. The scale next to the simulated beam is a measure of the amount of cracking in the concrete.

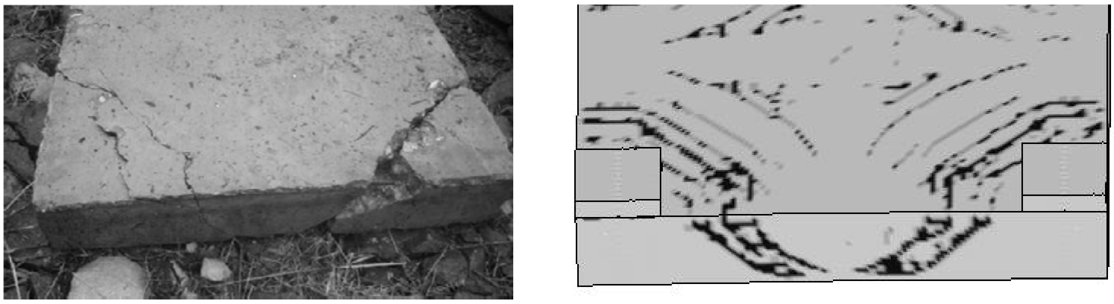

Figure 16. (a) Experimental result. (b) Cracking pattern predicted by BDM.

CONCLUSIONS

The investigation presented in this paper involves numerical simulations of reinforced concrete beams and slabs subjected to blast loads with the use of the analysis software LS-DYNA. The following conclusions were drawn:

- The results of the beam simulations show that the calculated deflections correspond very well to those obtained in the corresponding tests. This applies to both material models, and with the used material parameters.
- Both models were able to predict shear failures of the beams. Using the BDM resulted in cracking that was in excess of the test results. Simulations with the CSCM model resulted in cracking that corresponded well to that of the tested beams.
- The results of the slab simulations show that the BDM was able to predict the shear failure obtained in the tests. Diagonal cracks close to each support were clearly visible. However, simulations with the CSCM model only showed initiated shear cracks and fully developed flexural cracks at mid-span. Thus, the slabs were predicted to fail in flexure. The bending failure prediction of CSCM is attributed to its inaccurate response on tensile failures when the compressive stresses are relatively low. It is to note that this is a plasticity-based model, in which emphasis has been made in the proper definition of the compressive behaviour, which was not dominant in the slabs' detonation tests.
- The results show the importance of a material model being able to accurately capture cracks in concrete members. Without this ability, shear cracks and subsequent failures may be overlooked in analyses of blast loaded concrete structures.

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